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Optimum Flywheel Sizing for Parallel and Series Hybrid Vehicles

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OPTIMUM FLYWHEEL SIZING FOR PARALLEL AND SERIES HYBRID VEHICLES*

by

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Abstract

Flywheels have the possibility of providing high turnaround efficiency and high specific power output. These characteristics are very important for the successful manufacture of parallel and series hybrid vehicles, which have the potential for providing high fuel economy and very low emissions with range and performance comparable to today's light-duty vehicles.

Flywheels have a high specific power output, but relatively low specific energy output. Therefore, it is of importance to determine energy and power requirements for flywheels applied to light-duty vehicles. Vehicle applications that require an energy storage system with high power and low energy are likely to benefit from a flywheel.

In this paper, a vehicle simulation code and a flywheel model are applied to the calculation of optimum flywheel energy storage capacity for a parallel and a series hybrid vehicle. A conventional vehicle is also evaluated as a base-case, to provide an indication of the fuel economy gains that can be obtained with flywheel hybrid vehicles.

The results of the analysis indicate that the optimum flywheel energy storage capacity is relatively small. This results in a low weight unit that has a significant power output and high efficiency. Emissions generated by the hybrid vehicles are not calculated, but have the potential of being significantly lower than the emissions from the conventional car.

Introduction

Series and parallel hybrid vehicles have been built and analyzed for many years, Chang [1], Schreiber [2], Burke [3], with batteries providing energy storage. While appropriate as low-emission vehicles, battery hybrids often provide little improvement in fuel economy compared to conventional cars, due to the low specific power and low turnaround efficiency of most current batteries.

Flywheels have been recognized as devices that can be used in hybrid vehicles to provide high fuel economy, Smith [4]. Flywheels currently being developed have high efficiency and specific power, and a reasonable specific energy storage capacity. Application of these devices to vehicles makes series and parallel hybrid vehicles a more likely option, once the flywheel containment issues are well understood and solved.

A flywheel model has been developed based on projections for the performance of a flywheel design that is currently being tested, Post [5]. Table 1 shows the most important parameters for this model.

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Table 1. Projected performance parameters for flywheel model used in this analysis. Values include mass, containment, inverter and controller.

Specific energy, Wh/kg	20
Specific power, W/kg	3,300
Energy per unit volume, Wh/l	33
Maximum one-way efficiency, %	96
Stand-by losses at 0% SOC, W	50
Stand-by losses at 100% SOC, W	200

In this paper, the flywheel model is combined with a vehicle simulation code, Aceves [6] to study the flywheel energy storage capacity that is optimum for series hybrid and parallel hybrid vehicles. The results are considered to be useful in determining the design characteristics that may make a flywheel appropriate for vehicular application. A conventional vehicle is also evaluated, to provide an indication of the fuel economy gains that can be obtained with flywheel hybrid vehicles.

Vehicle Description

Table 2 lists the main characteristics of the conventional, parallel hybrid and series hybrid vehicles considered in this analysis. All the vehicles have good aerodynamics and low rolling friction. The conventional and the parallel hybrid cars use a 5-speed transmission, and the series hybrid uses a single-speed transmission. All the vehicles are required to meet the following minimum performance specifications: acceleration from 0 to 97 km/h (0-60 mph) in no more than 10 seconds; climbing a slope of at least 6% at a constant 97 km/h (60 mph) speed; and minimum range of 644 km (400 miles).

Table 2. Main parameters for conventional, parallel hybrid and series hybrid vehicles.

Vehicle parameter	conventional	parallel	series hybrid
frontal area, m^2	2.04	2.04	2.04
aerodynamic drag coefficient	0.24	0.24	0.24
coefficient of rolling friction	0.007	0.007	0.007
transmission efficiency	0.94	0.94	0.95
transmission gears	5	5	1
accessory load, W	1000	1000	1000
engine idling speed, rpm	750	750	-
launch engine RPM, maximum effort acceleration	3600	3600	-
regenerative braking	no	yes	yes
fraction of available energy recovered by regenerative braking, %	0	70	70
generator type	-	permanent magnet	permanent magnet
motor type	-	AC induction	AC induction
energy storage device	-	flywheel	flywheel
fuel	gasoline	gasoline	gasoline
energy penalty for engine cycle, kWh	-	-	0.05

The empty weight for the conventional car is set to 1000 kg, which is used as base case. This low weight is chosen because research programs such as PNGV (Partnership for a New Generation of Vehicles) are likely to result in weight reductions for future cars. Weight for the other two vehicles is calculated by replacing components, and adding or subtracting the weight of the components. A 30% structural penalty is added to the difference in power train weight, to take into account the need for a heavier structure that results from a heavier power train.

A performance map published in the literature for a recent gasoline production engine is used in this analysis, Thomson [7]. The production engine is a 4-cylinder, 2.3 liter engine. The vehicles analyzed in this paper are lighter and more aerodynamic than the production cars in which the engine has been used, and therefore the engine can be downsized to 3 or even 2 cylinders, especially for hybrid vehicles, in which the flywheel can be used to provide peak power when necessary. It is assumed that the engine performance maps for the 3-cylinder or 2-cylinder engines are obtained from the original map by multiplying the torque scale by the ratio of the number of cylinders in the downsized engine to the number of cylinders in the original engine (_ or _).

The number of engine cylinders is reduced to downsize the engine. However, the volume of the individual cylinders is kept constant in the analysis, because engine efficiency is often sensitive to the cylinder size (increasing as the cylinder size increases due to reduced heat transfer losses, Heywood [8]). This dependence would make it difficult to appropriately scale the engine map to different cylinder sizes.

A brief description of the operating strategies for the parallel and series hybrid vehicles is as follows: The parallel hybrid vehicle operates very similarly to a conventional car, except that a flywheel and a traction motor are used for complementing the power of the engine during sudden accelerations, and for regenerative braking. The use of the flywheel for power peaking allows a reduction in the size of the engine, which may therefore operate more efficiently than the engine used in the conventional car at the low-power conditions that constitute most of the urban and highway driving cycles. The engine is sized to provide the required performance during long hill climbs, for which the flywheel cannot provide the required energy. This engine sizing strategy results in a vehicle that responds the same way every time it is driven over the same roadway. The control strategy used for the flywheel consists of keeping it near 50% state of charge. In this way, the flywheel is always ready to provide energy for a sudden acceleration, and to absorb energy during regenerative braking. It is noted that there are many possible parallel hybrid control strategies. The 50% state of charge for energy storage was chosen as a simple strategy that accomplishes both engine downsizing and regenerative braking. It is unlikely that this is the optimum parallel strategy.

The series hybrid vehicle operates with an engine in an on-off mode, with no mechanical link between the engine and the wheels. An electric motor provides the tractive power. When the engine is running, it drives a generator that supplies electricity to both the electric motor and the flywheel energy storage system. When the storage system is fully charged, the engine is turned off, and the storage system provides all the energy required for traction and accessories. Series hybrid vehicles have high fuel economy because the engine is operated at a high efficiency condition without ever idling. Spark ignition engines can therefore be run unthrottled thus avoiding pumping losses. Engines in series hybrids operate most of the time at a low power, high efficiency condition, at constant speed and load. When additional power is required during long hill climbs, the engine can be operated at a high power level, possibly at a lower efficiency. The flywheel provides the power for sudden accelerations, and the engine is again sized for providing the required performance for long hill climbs.

The engine in a series hybrid vehicle may operate at reduced efficiency when it is started cold, because of increased friction; and the engine may have to be cold-started frequently due to the on-off operation mode. In addition to efficiency losses, cold starts may also result in high emissions, if the catalytic converter cools down during the off-cycle. Considering that low emissions are an important incentive for developing series hybrid vehicles, it is desirable to electrically heat the catalytic converter before starting the engine. To take into account efficiency losses and energy required for heating the catalytic converter, an energy penalty of 0.05 kWh, Hamai [9] is assessed to the system every time the engine is turned on.

Results

The results of the analysis are listed in Table 3. The parallel hybrid car has almost the same weight as the conventional car. The weight of the added components (flywheel and motor) is compensated by the reductions in weight that result by downsizing the engine, transmission and fuel tank. The series hybrid vehicle weighs almost 200 kg more than the other two vehicles, primarily due to its need for a flywheel with greater energy storage capacity.

Table 3. Results of the analysis for the conventional vehicle and optimum designs for the parallel hybrid and series hybrid vehicles.

Vehicle parameter	conventional	parallel hybrid	series hybrid
test weight, (empty weight + 136 kg)	1136	1120	1314
number of engine cylinders	3	2	2
maximum engine power, kW	82.5	55	55
gasoline tank storage capacity, liters (gal)	40.0 (10.6)	30.2 (8.0)	28.4 (7.5)
motor maximum short-term torque, Nm	-	58	190
motor maximum speed, rpm	-	11000	11000
optimum flywheel energy storage, kWh	-	0.1	1.5
flywheel maximum power, kW	-	20	100
average engine efficiency, urban cycle, %	19.1	20.0	33.5
average engine efficiency, highway cycle, %	21.3	25.1	33.5
fuel economy[1], urban cycle, km/liter (mpg)	13.6 (31.9)	18.8 (44.3)	20.5 (48.3)
fuel economy[1], highway cycle, km/l (mpg)	20.7 (48.6)	25.8 (60.7)	25.9 (61.0)
fuel economy[1], combined cycle, km/l (mpg)	16.1 (37.8)	21.4 (50.4)	22.7 (53.3)
time for 0-97 km/h (0-60 mph), s	8	10.0	10.0
maximum climbing slope at 97 km/h, %	15.8	11.0	6.0
vehicle range, combined cycle, km (miles)	644 (400)	644 (400)	644 (400)

Due to reduced vehicle weight, the conventional vehicle only requires a 3-cylinder engine to provide the required acceleration performance. This engine is therefore greatly oversized for providing the required hill climbing performance (15.8% grade instead of 6% grade). A 2-cylinder engine does not provide enough power for driving the conventional vehicle through the urban cycle, and results in a time of 12.4 s for the 0-97 km/h maximum effort acceleration, and therefore it is not an acceptable option. It could be possible to downsize the cylinders to obtain a 3-cylinder engine that provides a better match to the power requirements of the conventional car. However, as previously stated, this possibility is not considered in this paper, because engine efficiency often drops as the size of the cylinders is reduced.

The hybrid vehicles only require a 2-cylinder engine, since the flywheel can be used for providing the power for maximum effort acceleration. Minimum engine power requirements are set for the hill climb, since flywheel energy may not be enough for climbing very long hills. The engine for the parallel hybrid is oversized for the hill climb. Again, the cylinder size could be reduced to obtain a better match, but it is not done due to the difficulty in scaling the engine map.

Fuel economy for the series hybrid is highest because the engine always operates at its peak efficiency (33.5%). The difference in fuel economy between the parallel hybrid and the conventional car is due in part to the higher average engine efficiency that results from downsizing the engine, and in part due to the regenerative braking that can be done in the hybrid. The volume and weight of the gasoline tank for each vehicle is adjusted to meet the desired range.

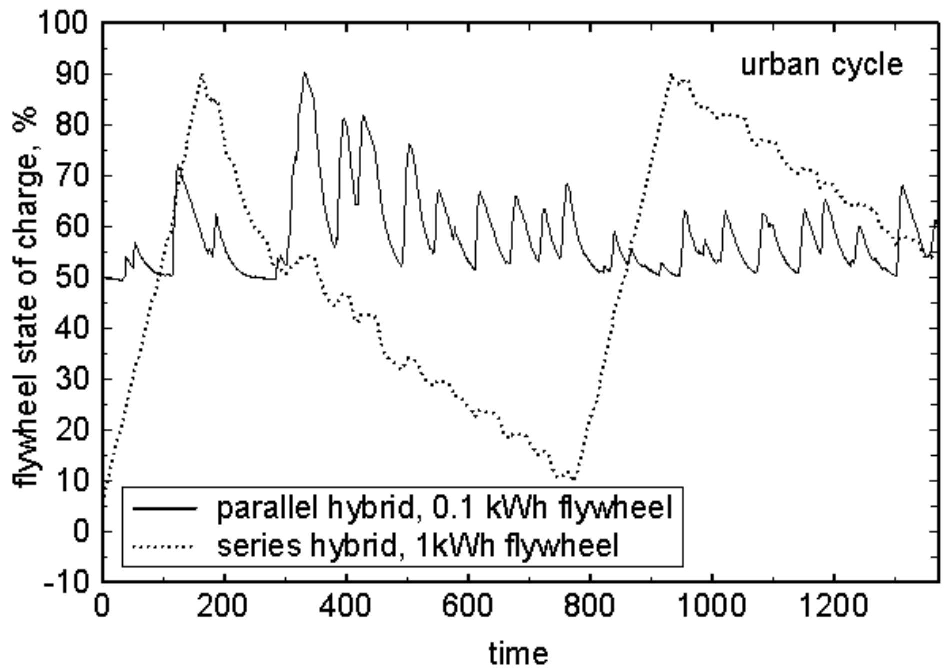

Figure 1. Flywheel state of charge for the parallel hybrid and the series hybrid vehicles on the EPA urban driving cycle. For the parallel hybrid, the flywheel is kept near 50% state of charge, ready to store energy during regenerative braking, or provide energy for a sudden acceleration. For the series hybrid, the engine runs at constant power until it fully charges the flywheel.

Emissions are not calculated in this analysis, but they are expected to be low for the hybrid vehicles. The parallel hybrid vehicle uses the flywheel to provide for peak power, and therefore emissions due to enrichment at maximum power can be reduced or avoided. The series hybrid vehicle operates with the engine at constant speed and torque, and therefore the fuel-air mixture can be set very precisely to the optimum catalytic converter operating point. A preheated catalyst should reduce or eliminate cold start emissions.

The optimum flywheel energy storage capacity for the parallel hybrid is only 0.1 kWh, while the optimum capacity for the series hybrid is 1.5 kWh. Figures 1 through 4 and the discussion included in the following paragraphs illustrate the trade-off that determines the optimum flywheel capacity for both vehicles.

Figure 1 shows flywheel state of charge for the parallel hybrid and the series hybrid vehicles along the urban driving cycle. For the parallel hybrid, the flywheel is kept at about 50% state of charge, ready to store energy during regenerative braking, or provide energy for a sudden acceleration. The flywheel state of charge increases due to regenerative braking, and drops when power is extracted from the flywheel. Flywheel stand-by losses also tend to reduce the state of charge. For the series hybrid, the engine runs at constant power until it fully charges the flywheel, which takes about 150 seconds for a 1 kWh flywheel. The flywheel then provides all the energy requirements, discharging in about 600 seconds. The engine is then turned on again to repeat the cycle.

As shown in Figure 1, the flywheel for the parallel hybrid vehicle almost reaches maximum capacity after a sudden deceleration about 400 s into the driving cycle. Reducing the flywheel capacity under 0.1 kWh would result in a fully charged flywheel during sudden stops, and would therefore reduce the amount of the energy that can be recovered through regenerative braking. More importantly, a reduced flywheel capacity may result in a reduced acceleration performance for the vehicle, because the energy stored in the flywheel may run out during a maximum-effort acceleration. These effects are illustrated in Figure 2. The figure shows combined cycle fuel economy in km/liter, and time for 0-97 km/h (60 mph) maximum effort acceleration in seconds, for the parallel hybrid vehicle. Fuel economy decreases slowly as the energy storage capacity increases from 0.1 kWh due to the added flywheel weight. Fuel economy also drops as the fuel economy is reduced from 0.1 kWh due to the impossibility to recover all the available regenerative braking. Time for maximum effort acceleration increases as the energy storage capacity decreases because the flywheel runs out of energy during the acceleration. The limiting case of zero flywheel storage capacity corresponds to a conventional vehicle with a 2-cylinder engine and no flywheel, which, as previously discussed, can reach 97 km/h in 12.4 s. The acceleration calculations assume that the flywheel initially has a 25% state of charge. Note that the 2-cylinder engine at full power can fully charge the flywheel in only 6 seconds.

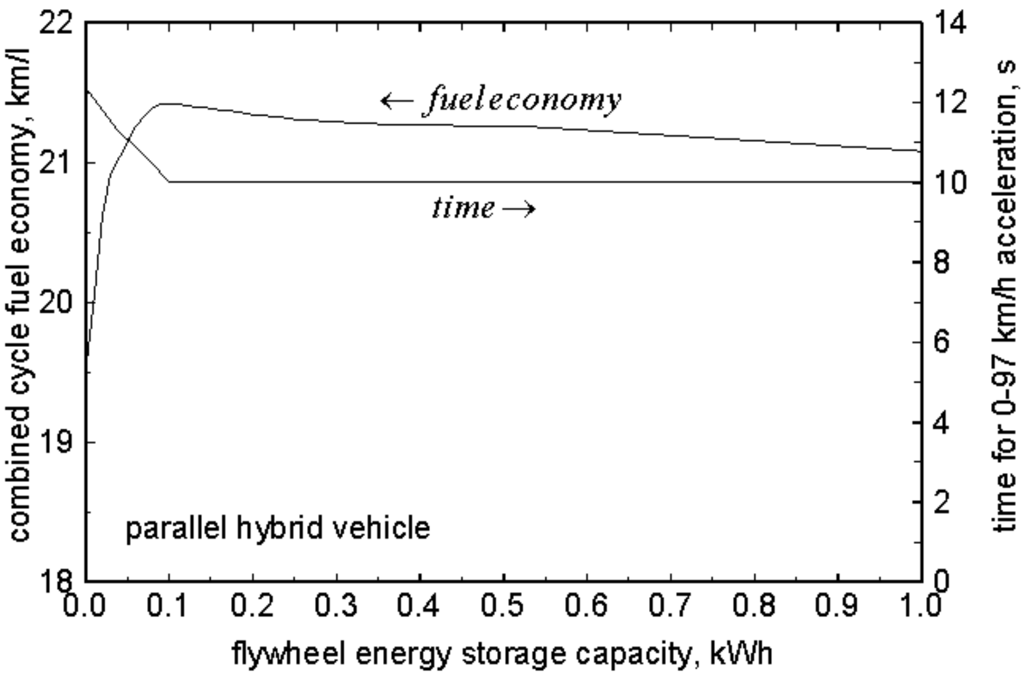

Figure 2. Combined cycle fuel economy in km/liter, and time for 0-97 km/h (60 mph) maximum effort acceleration in seconds, for the parallel hybrid vehicle. The acceleration calculations assume that the flywheel initially has a 25% state of charge.

The motor and flywheel power for the parallel hybrid vehicle are sized for complementing the engine power when peak performance is required, and are rather low (20 kW). This power is not enough to recover all the energy available during regenerative braking, especially during very sudden decelerations. However, sudden accelerations are relatively rare, and it is considered that the lighter weight of the low power components compensates for the energy losses.

Figures 3 and 4 illustrate the trade-off that determines optimum flywheel energy storage capacity for the series hybrid vehicle. Figure 3 shows vehicle fuel economy as a function of flywheel energy storage capacity. The figure shows two curves, corresponding to flywheels with specific energy storage capacities of 20 Wh/kg (the base case), and 10 Wh/kg, included here to show the effect of a heavier flywheel on fuel economy. Fuel economy for the base case reaches its maximum at about 1.5 kWh. As the flywheel capacity increases from this point, the increased weight of the flywheel reduces the fuel economy of the vehicle. Reducing the flywheel size from its optimum capacity results in increased cyclic losses due to cold starts and catalytic converter preheating. The vehicle with the heavier flywheel has a maximum fuel economy of 21.9 km/l (51.5 mpg), at an optimum flywheel capacity of approximately 1 kWh. Both curves are very flat near the optimum, so that the capacity of the flywheel can be reduced to reduce its cost and volume with negligible losses in fuel economy.

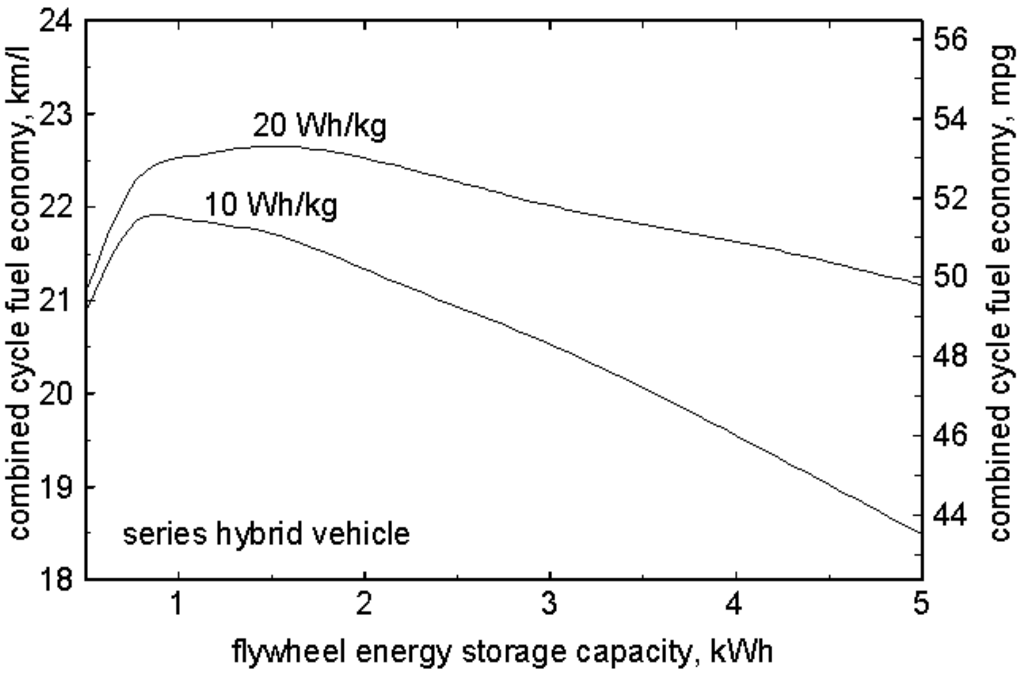

Figure 3. Vehicle fuel economy as a function of flywheel energy storage capacity. The figure shows two curves, corresponding to flywheels with specific energy storage capacities of 20 Wh/kg (the base case), and 10 Wh/kg, included here to show the effect of a heavier flywheel on fuel economy.

Figure 4 is included to illustrate the trade-off that determines the optimum flywheel energy storage capacity for the series hybrid vehicle. The figure shows flywheel system weight (including flywheel, containment and power electronics) and average engine on- and off-times as a function of flywheel energy storage capacity. Flywheel weight increases linearly with flywheel capacity. Increases in vehicle weight are due to the weight increases of the flywheel, the motor (to provide constant performance even as the vehicle weight increases), and the vehicle chassis, required to support heavier vehicle components. Average operating time for the engine and average off-cycle also increase linearly with flywheel energy storage capacity. Operation period for the engine is 93 s for a 0.5 kWh flywheel. From this point, engine operating period increases to almost 15 minutes for a 5 kWh flywheel. The off-cycle time for the 5 kWh flywheel is approximately 1 hour.

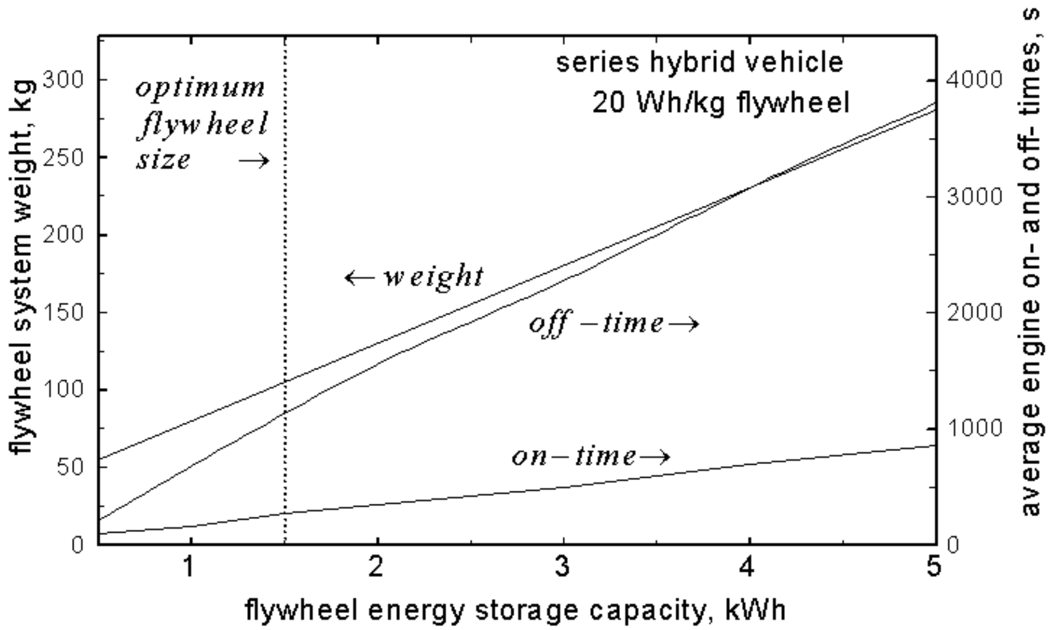

Figure 4. Flywheel system weight (including flywheel, containment, and power electronics) and average engine on- and off-times as a function of flywheel energy storage capacity.

Conclusions

This paper has simulated three vehicles: a conventional, a parallel hybrid vehicle and a series hybrid vehicle. The hybrid vehicles use a flywheel for energy storage. The flywheel has the potential of providing high efficiency and specific power output, which are required for obtaining a high fuel economy and good performance in hybrid vehicles.

This paper presents an optimization for maximum fuel economy of the flywheel energy storage capacity for the parallel and the series hybrid vehicles. The optimum flywheel energy storage capacity for the parallel hybrid vehicle is found to be about 0.1 kWh. This value is very small because the flywheel in a parallel hybrid vehicle is only used to complement the engine power when peak performance is required. The series hybrid vehicle has an optimum flywheel energy storage capacity of about 1.5 kWh. This value is determined by a trade-off between flywheel weight and the energy penalty that results from cycling the engine on and off.

The results of the analysis are expected to indicate appropriate flywheel sizes for vehicular applications. It appears that flywheels with relatively small energy storage capacity are most appropriate, leaving the engine to provide power to the vehicle during long hill climbs.

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